32 Years of Challenging Experimental Physics

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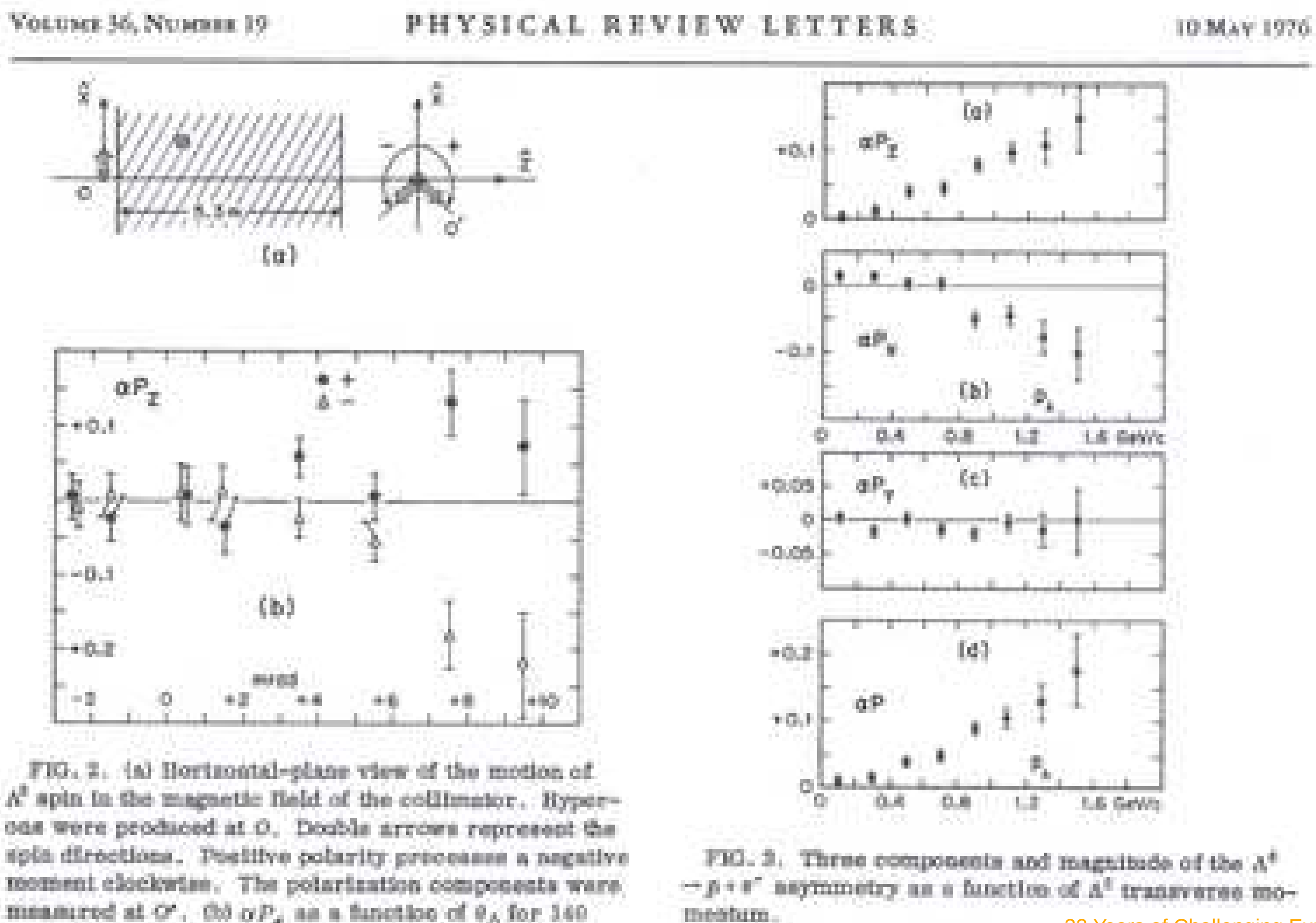
Hyperon physics

- An experiment designed for an accurate determination of hyperon magnetic moments led to unexpected first discovery of the Λ polarization in inclusive production.
- It has opened up a new field of search for transverse single-spin asymmetries (SSA) in hyperon inclusive production.
- Systematic studies of energy dependence, target dependence for neutral, charged hyperon and antihyperon production, were undetaken.
- Many new transverse SSA were found.

G. Bunce et al., Phys. Rev. Lett. 36, 1113 (1976)



Volume 36, Number 19 PHYSICAL REVIEW LETTERS 10 May 1976

FIG. 2. (a) Horizontal-plane view of the motion of Λ^0 spin in the magnetic field of the collimator. Hyperons were produced at O. Double arrows represent the spin directions. Positive polarity precesses a negative moment clockwise. The polarization components were measured at O'. (b) αP_z as a function of θ_Λ for 160

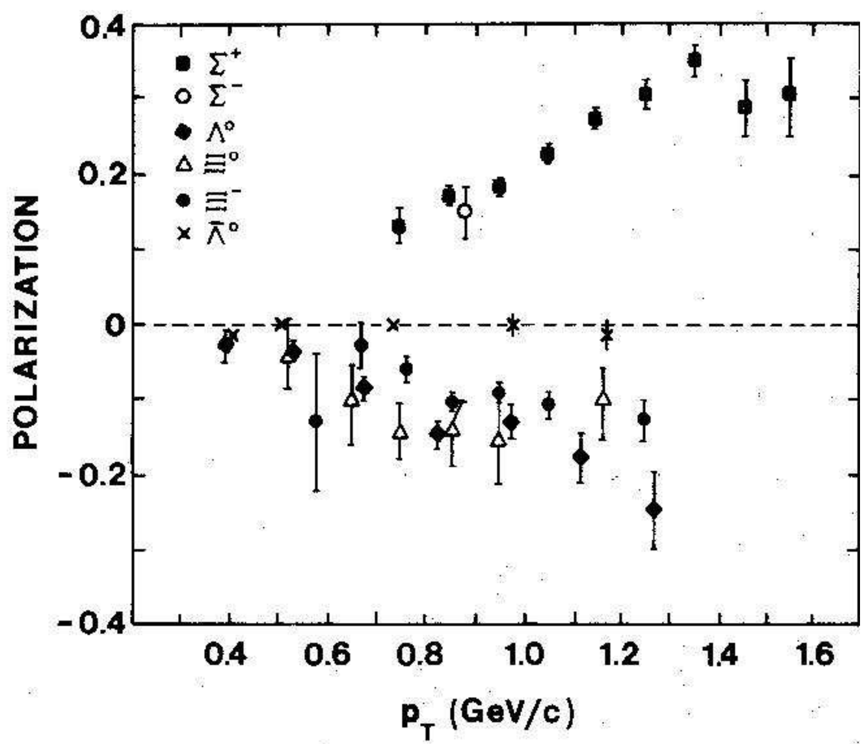
FIG. 3. Three components and magnitude of the $\Lambda^0 \to p + \pi^-$ asymmetry as a function of Λ^0 transverse momentum.

Following FNAL 1976: many new SSA measurements

HYPERON POLARIZATION (SSA) FIRST DISCOVERED in 1976 AT FNAL

in Λ production. Confirmed at 24 GeV/c at CERN in 1977

New surprises since 1976: A_N in hyperon inclusive production at FNAL



Following FNAL 1976: many new SSA measurements

Main features of these data

Let us briefly recall the main characteristics of these proton induced data, which exhibit some interesting regularities as well as puzzling features:

- i) the invariant cross section $Ed^3\sigma/dp^3$ depends, to a good approximation, only on x_F^Λ, the fraction of incident proton momentum carried by the Λ in the beam direction (in the center of mass (*c.m.*) system), and A_N^Λ, the Λ transverse momentum, and does *not* depend on the *c.m.* energy $\sqrt{s}$.
- ii) the transverse SSA A_N^Λ is *negative* with respect to the direction $\vec{n} = \vec{p}_{inc} \times \vec{p}_\Lambda$.
- iii) A_N^Λ is almost energy and target independent for an incident energy ranging from 12 GeV/c on a Tungsen target up to 2000 GeV/c at ISR.
- iv) for p_T^Λ below 1 GeV/c or so, the magnitude of A_N^Λ is approximately linear in p_T^Λ, with a slope increasing with x_F^Λ.
- v) for p_T^Λ above 1 GeV/c, the magnitude of A_N^Λ is independent of p_T^Λ, up to $p_T^\Lambda \sim 3.5\ GeV/c$ and approximately linear with x_F^Λ.
  We also have data on other hyperon SSA at FNAL energy, where one observes, with respect to A_N^Λ, an effect of opposite sign for $\Sigma^\pm$ and same sign for Ξ^- and Ξ^0. However it seems that $A_N^{\Xi^-}$ does *not* increase with energy, whereas $A_N^{\Sigma^+}$ decreases with energy.

Following FNAL 1976: many new SSA measurements

Main features of these data

- Finally, the situation of the antihyperon SSA is very puzzling since, on the one hand, $A_N^{\Lambda} \sim A_N^{\Xi^0} \neq 0$ and $A_N^{\bar{\Lambda}} \sim A_N^{\bar{\Xi}^0} = 0$, but on the other hand, $A_N^{\bar{\Sigma}^-} \sim A_N^{\Sigma^+}$ and $A_N^{\bar{\Xi}^+} \sim A_N^{\Xi^-}$.
- On the theoretical side several dynamical models have ben proposed:

  - Semiclassical models (Lund model, Recombination model, Berlin model).

  They essentially ignore the unpolarized cross section and try to relate different SSA.

  Not very convincing.

  - Regge type models essentially for the Λ case.

  Can describe the cross section as well as A_N^{Λ} but no possible extension to the other hyperons.
- Needless to say, all these peculiarities of the data remain to be understood and according to Bj:

"‘ THEY CONSTITUTE A REAL CHALLENGE FOR THE THEORY. "‘

Transverse single-spin asymmetries A_N

What is a transverse single-spin asymmetry (SSA)?

Consider the $a+b$ collision with one particle of momentum $\overrightarrow{p}$, carrying a transverse spin $\overrightarrow{s_T}$ and producing an outgoing hadron with momentum $\overrightarrow{k}$. The SSA defined as

$$A_N = \frac{d\sigma(\overrightarrow{s_T}) - d\sigma(-\overrightarrow{s_T})}{d\sigma(\overrightarrow{s_T}) + d\sigma(-\overrightarrow{s_T})}$$

is zero, unless the cross section contains a term $\overrightarrow{s_T} \cdot \overrightarrow{n}$, where $\overrightarrow{n} = (\overrightarrow{p} \times \overrightarrow{k})$
It can be shown that this requires the existence of an helicity flip and final state interactions, which generate a phase difference between the flip and the non-flip amplitudes, to avoid violation of time reversal invariance.

Some exemples

1)- Two-body reactions $a + b^{\uparrow} \longrightarrow a' + b'$
The scattering amplitude reads $f_+ + f_- \overrightarrow{\sigma} \cdot \overrightarrow{n}$. Here f_+ and f_- are non-flip and flip helicity amplitudes, respectively. We will consider two relevant observables $d\sigma/dt = |f_+|^2 + |f_-|^2$ and $\mathrm{A}_N = \frac{2Im(f_+ f_-^*)}{|f_+|^2+|f_-|^2}$
- $A_N \neq 0$ only if $f_- \neq 0$ and has a phase difference with f_+.

- One also has a kinematic constraint, $A_N = 0$ in the forward direction, i.e. for $k_T = 0$.

Transverse single-spin asymmetries A_N

2)- One particle inclusive reactions $a + b^{\uparrow} \to c + X$

It is directly related to M which denotes the absorptive part of the *forward* amplitude for the elastic $3 \to 3$ reaction $a + b + \bar{c} \to a + b + \bar{c}$. It has the general expression $M = H_1 + H_2 \overrightarrow{\sigma} \cdot \overrightarrow{n}$.

Here H_1 and H_2 are non-flip and flip amplitudes, respectively.

We will consider 2 relevant observables:

$$\frac{Ed^3\sigma}{d^3p} = H_1 \qquad and \qquad A_N = \frac{H_2}{H_1}$$

- $A_N \neq 0$ only if $H_2 \neq 0$. According to a NAIVE argument, one should expect $A_N = 0$, since one is summing over many different inelastic channels X, which should have SSA of random magnitudes and signs, such that the sum will average to zero.

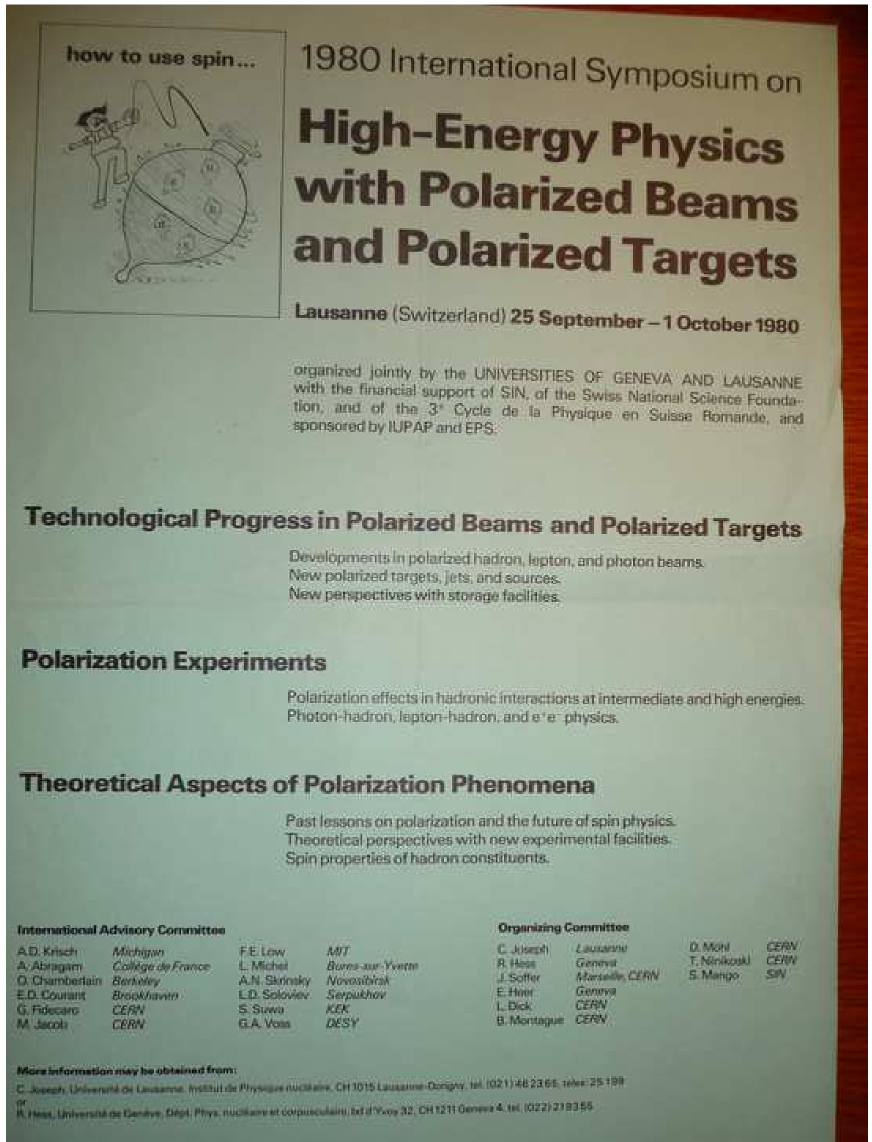
- Also a kinematic constraint, $A_N = 0$ in the forward direction, i.e. for $k_T = 0$.

Some Famous Spin Symposium

- Lausanne 1980.
- BNL 1982
- Marseille 1984
- Minneapolis 1988

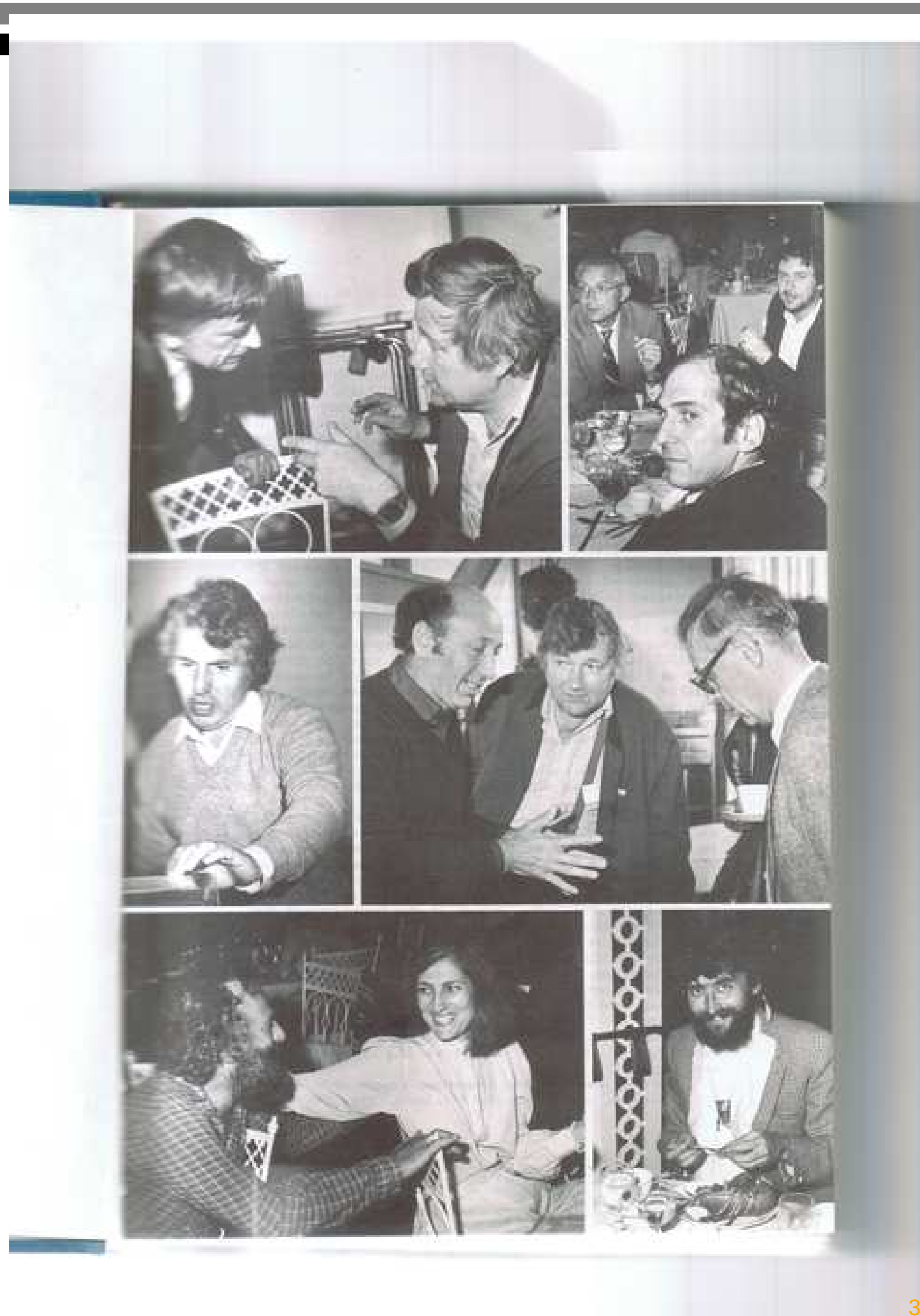
SPIN 80 Lausanne

G. Bunce: Polarization in inclusive production at Brookhaven

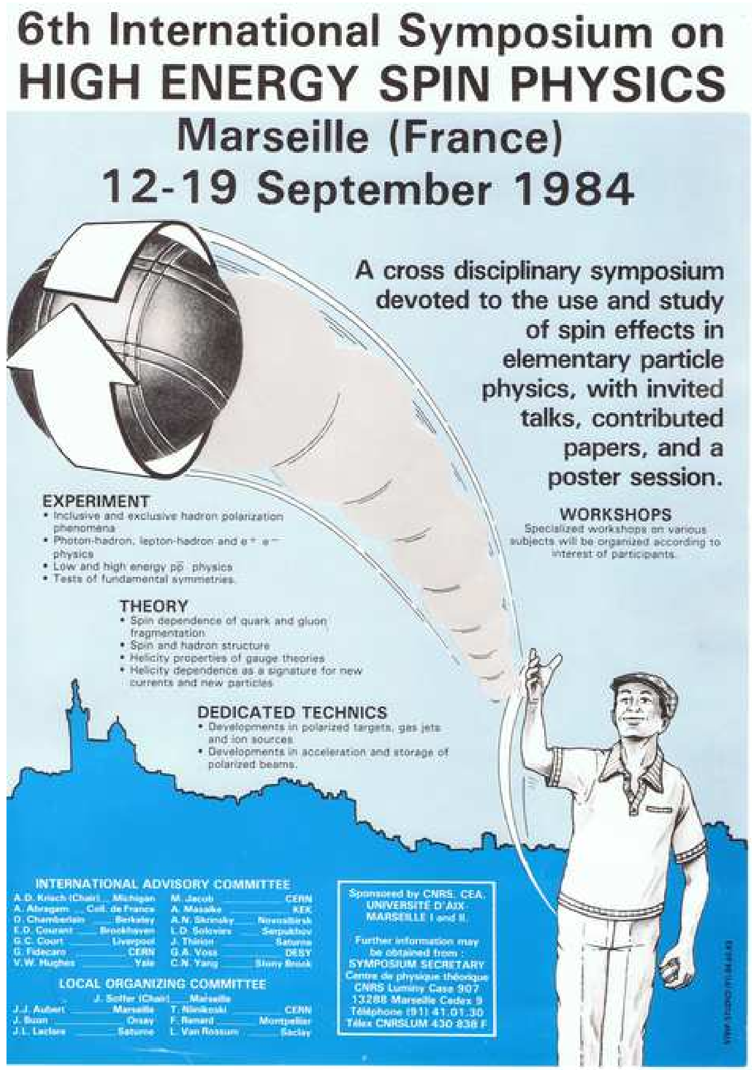


SPIN 82 BNL : a great Symposium organized by Gerry

SPIN 82 BNL : a great Symposium organized by Gerry



SPIN 84 Marseille



SPIN 84 Marseille : Gerry found a new way to use SPIN !

SPIN 84 Marseille : Gerry found a new way to use SPIN !

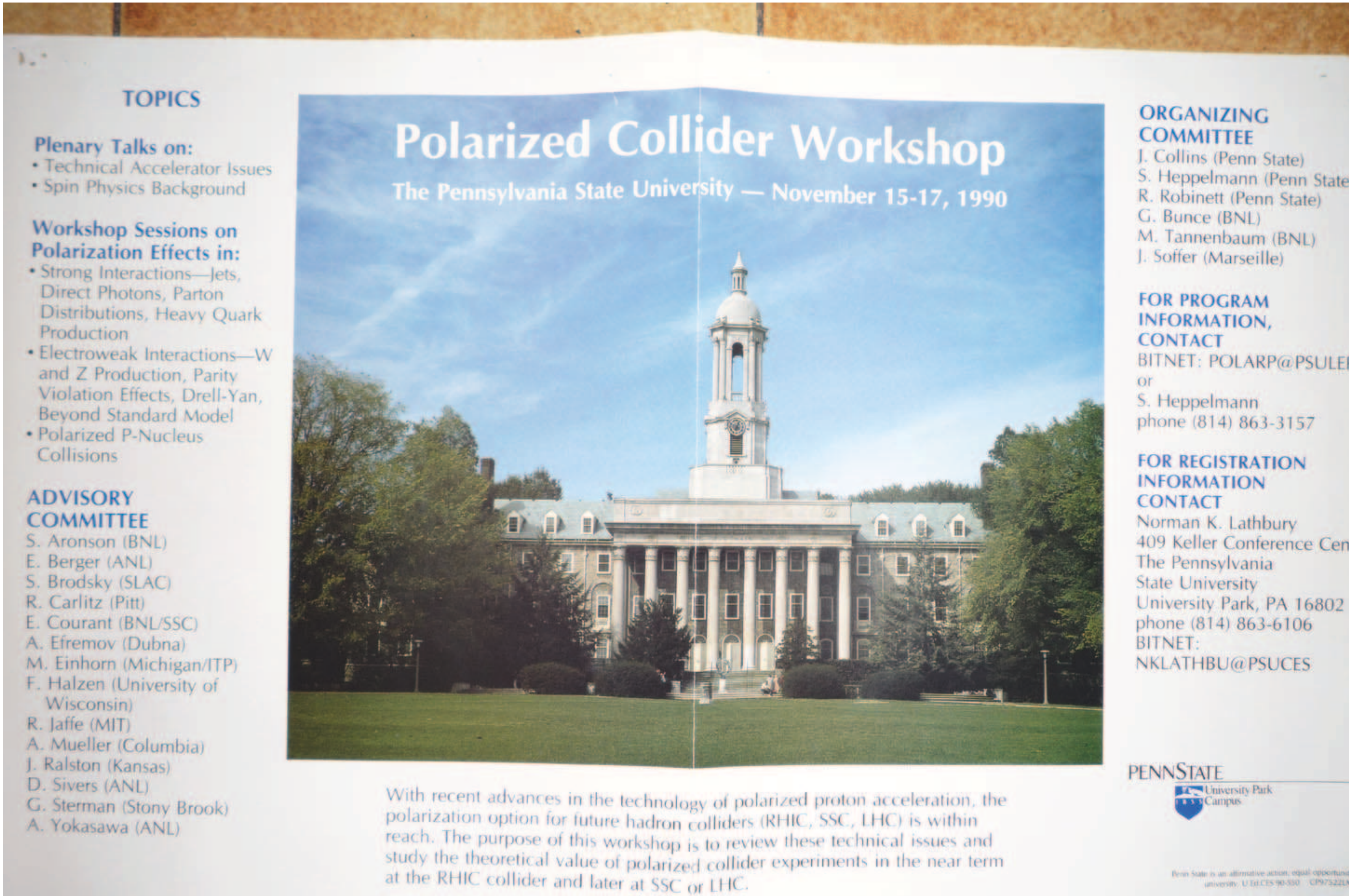
SPIN 84 Marseille : Gerry found a new way to use SPIN !

SPIN 88 Minneapolis - Summary of the Symposium: Gerry BUNCE

A milestone for high energy spin physics

- Penn State 1990
- The RHIC Spin Collaboration (RSC)
- Polarized protons at RHIC

Penn State 1990



TOPICS

Plenary Talks on:

- Technical Accelerator Issues
- Spin Physics Background

Workshop Sessions on Polarization Effects in:

- Strong Interactions—Jets, Direct Photons, Parton Distributions, Heavy Quark Production
- Electroweak Interactions—W and Z Production, Parity Violation Effects, Drell-Yan, Beyond Standard Model
- Polarized P-Nucleus Collisions

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Polarized Collider Workshop

The Pennsylvania State University — November 15-17, 1990

With recent advances in the technology of polarized proton acceleration, the polarization option for future hadron colliders (RHIC, SSC, LHC) is within reach. The purpose of this workshop is to review these technical issues and study the theoretical value of polarized collider experiments in the near term at the RHIC collider and later at SSC or LHC.

ORGANIZING COMMITTEE

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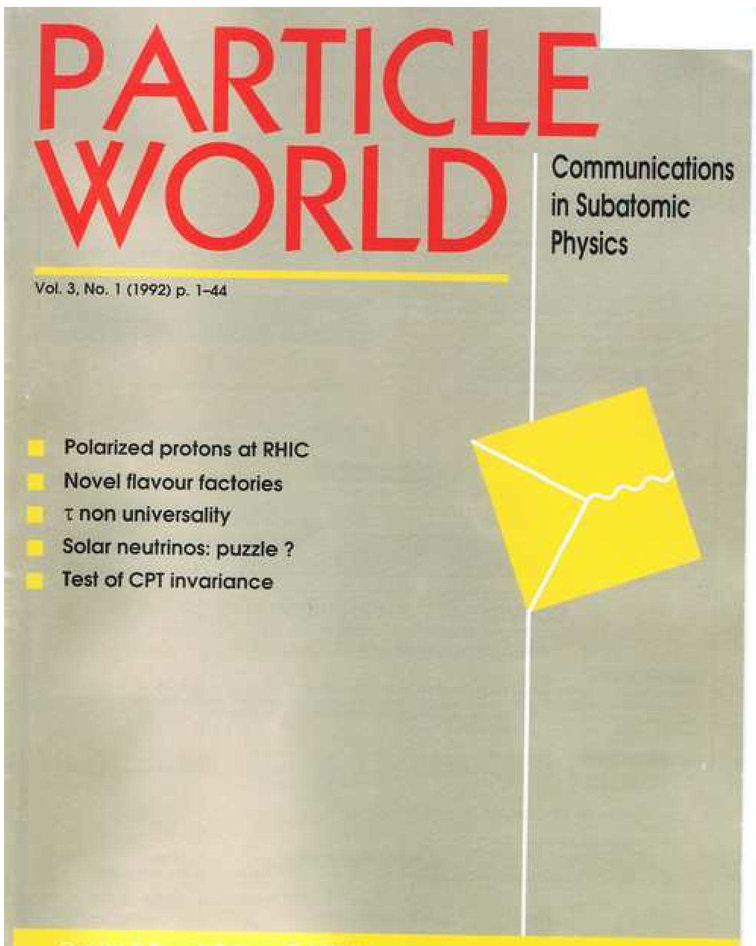
Following Penn State 1990: the RHIC Spin Collaboration



A R T I C L E

POLARIZED PROTONS AT RHIC

G. Bunce, J. Collins, S. Heppelmann, R. Jaffe, S.Y. Lee, Y. Makdisi, R.W. Robinett, J. Soffer, M. Tannenbaum, D. Underwood and A. Yokosawa

Abstract

Recent technical developments in the acceleration of polarized protons, using so-called Siberian snakes, now allow for the achievement of polarized proton-proton collisions at collider energies. We review the machine physics of achieving such collisions and describe a comprehensive program of spin physics which can be carried out at the RHIC facility using polarized pp collisions.

1. Introduction

The hugely successful program of QCD and electroweak tests at the hadron colliders at CERN and FNAL has provided a wealth of information on the Standard Model of particle physics. Tests involving jets (single and multi-jet events), direct photons, Drell–Yan weak boson production, and heavy quark and quarkonium production have probed the structure of the QCD hard-scatterings, often beyond leading order, and have yielded additional information on the parton structure of the proton itself.

One aspect of our understanding which has not benefitted from such experiments at high-energy colliders, however, is the area of spin physics, both the spin structure of the proton itself and the spin-dependence of the fundamental interactions.

Polarized pp collisions, which can address both issues, have previously been restricted to relatively low-energy (by collider standards) fixed-target experiments. So, spin, although historically central to the development of particle physics, has occasionally been relegated to a "soft physics" compartment in our field, despite indisputably large effects seen in many different experiments. At issue has been the interpretation whether a perturbative QCD analysis is possible or whether a complete understanding of non-perturbative effects is necessary.

With the successful tests of the Siberian snake concept [1], it now seems clear that a polarization option at a hadron collider, especially the Relativistic Heavy Ion Collider (RHIC) at BNL, is now a definite possibility [2–5]. A comprehensive program of experiments at such a facility would allow one to measure the spin-dependent parton distributions of the proton (both longitudinal and transverse) and would help to resolve any "spin crisis" raised by some theoretical interpretations of the much discussed Electromagnetic Calorimeter (EMC) experiments on polarized lepton–nucleus scattering [6]. Furthermore, it would provide fundamental spin tests of QCD and the electroweak interactions not accessible to unpolarized colliders, probing the helicity structure of the matrix elements of the fundamental hard scattering processes. Finally, the high energy and luminosity of such a machine would guarantee that a perturbative QCD approach would be applicable and would also be sufficient to produce high p_T jets and weak bosons copiously while at the same time ensuring that the contributing quark processes are in a region of documented high polarization. In these regards, a RHIC spin program will be unique.

Tests using polarized beams and targets at fixed-target energies involving direct photons and quarkonium production have been put forth as possible probes of the longitudinally polarized gluon distributions. The relatively low energies involved at presently envisaged polarized fixed-target facilities put the proposed experiments near the limit of applicability of perturbative QCD. In contrast, polarized pp collisions at RHIC, at collider energies ($\sqrt{s} = 50 - 500$ GeV) and with high luminosity (reaching $\mathcal{L} = 2.10^{32}$ cm^{-2}s^{-1}) would provide a huge sample of large transverse momentum events to which perturbative QCD would be just as applicable as at existing unpolarized machines. Furthermore, this can likely be achieved while providing $\sim 70\%$ polarization in each beam. Even with limited running time (say one month a year), this could yield well over 50 pb^{-1} of data and so would allow for high statistics studies of QCD and electroweak phenomena [5] and their spin dependence at a previously unattained level.

Besides being of unquestioned importance in its own right, such a program of collider spin physics is a crucial step in the assessment of the possible importance of polarization options at future supercolliders such as SSC or LHC. Given the extent to which the particle-physics community is committed to high-energy collider physics, it is of utmost importance that the parton content of the proton, including its spin dependence, be understood and it seems that a polarized RHIC facility would be the ideal machine for economically pursuing this program.

Motivated by these possibilities, a number of experimentalists, particle and nuclear theorists, and machine physicists have formed the RHIC Spin Collaboration (RSC) [7] to develop a comprehensive and compelling program of spin physics for RHIC. Some aspects of the physics prospects for such a facility have been discussed elsewhere [4,8,9] and in this article we will review various components of the proposal to achieve a program of polarized pp collisions at the RHIC. In sect. 2 we describe

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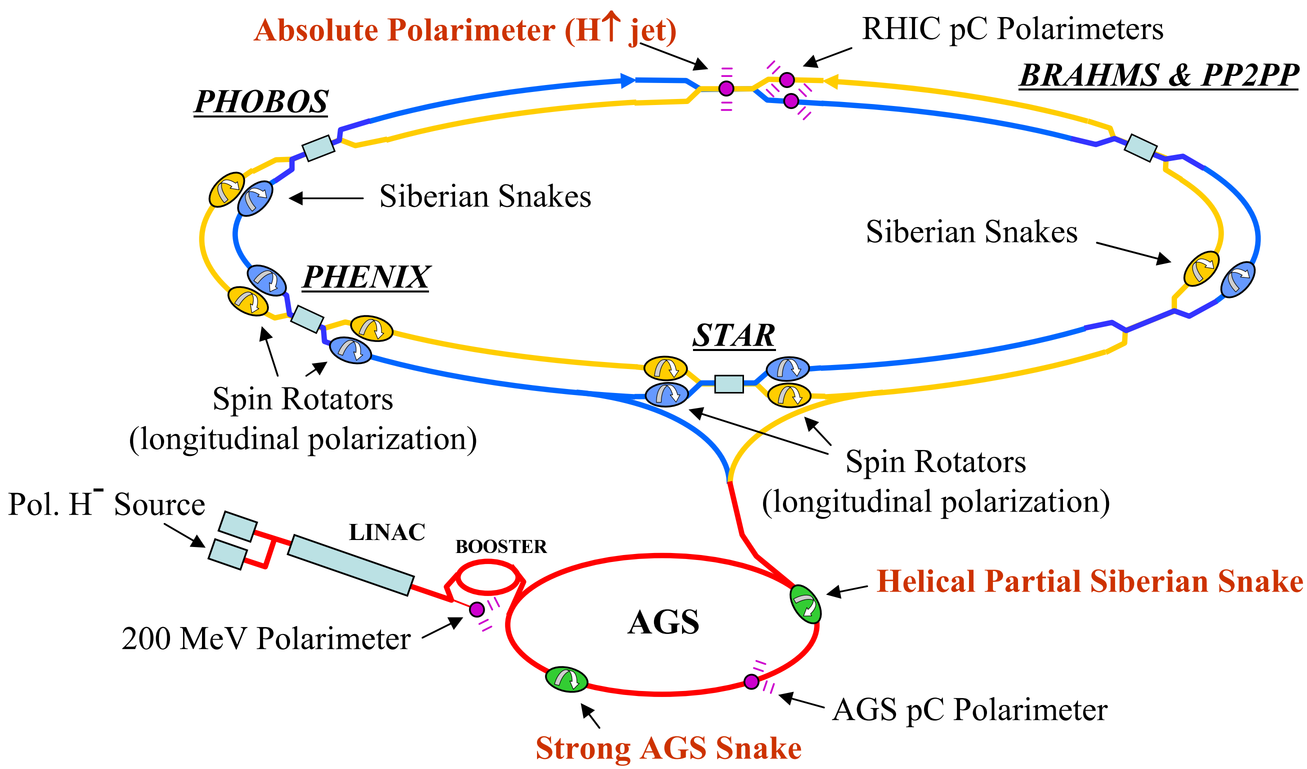
Particle World, Vol. 3, No. 1, p. 1-12, 1992.

From the RSC to the RHIC spin programme

RHIC Polarized Collider



2006: 1 MHz collision rate; P=0.6

Some interesting AGS results

- Exclusive reactions near 90°
- SSA for inclusive π production

AGS Results: Exclusive reactions at large angles

PHYSICAL REVIEW D VOLUME 49, NUMBER 1 1 JANUARY 1994

Comparison of 20 exclusive reactions at large t

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(Received 28 May 1993)

We report a study of 20 exclusive reactions measured at the AGS at 5.9 GeV/c incident momentum, 90° center of mass. This experiment confirms the strong quark flow dependence of two-body hadron-hadron scattering at large angle. At 9.9 GeV/c an upper limit had been set for the ratio of cross sections for $(\bar{p}p \to \bar{p}p)/(pp \to pp)$ at 90° c.m., with the ratio less than 4%. The present experiment was performed at lower energy to gain sensitivity, but was still within the fixed angle scaling region. A ratio $R(\bar{p}p/pp) \approx 1/40$ was measured at 5.9 GeV/c, 90° c.m. in comparison to a ratio near 1.7 for small angle scattering. In addition, many other reactions were measured, often for the first time at 90° c.m. in the scaling region, using beams of $\pi^{\pm}$, $K^{\pm}$, p, and $\bar{p}$ on a hydrogen target. There are similar large differences in cross sections for other reactions: $R(K^-p \to \pi^+\Sigma^-/K^-p \to \pi^-\Sigma^+) \approx 1/12$, for example. The relative magnitudes of the different cross sections are consistent with the dominance of quark interchange in these 90° reactions, and indicate that pure gluon exchange and quark-antiquark annihilation diagrams are much less important. The angular dependence of several elastic cross sections and the energy dependence at a fixed angle of many of the reactions are also presented.

PACS number(s): 13.75.−n, 13.85.Dz, 13.85.Fb

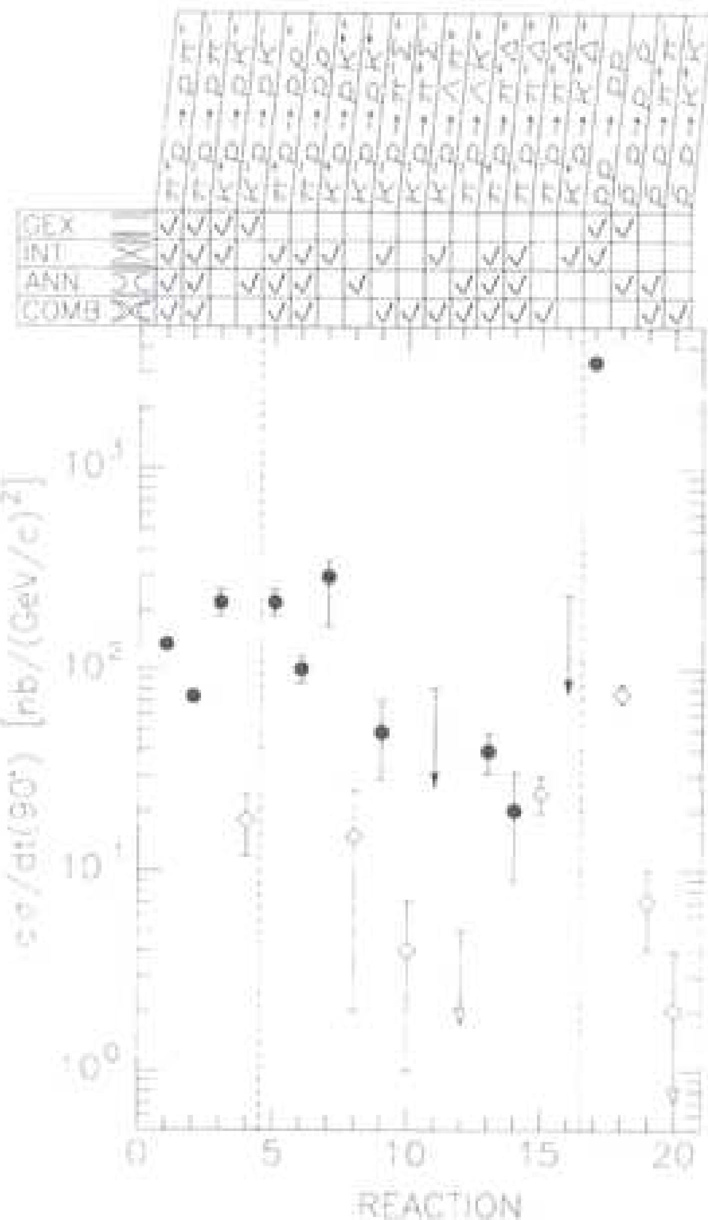
AGS Results: Exclusive reactions at large angles

FIG. 26. The scaling between E755 and E838 has been calculated for eight meson-baryon and 2 baryon-baryon interactions at $\theta_{c.m.} = 90°$. The beam momentum for E838 was 5.9 GeV/c, corresponding to $s = 11.9$ GeV^2 for meson-baryon reactions and $s = 12.9$ GeV^2 for baryon-baryon reactions. For the 9.9 GeV/c momentum of E755, the corresponding values of s are 19.6 and 20.5 GeV^2.

Reaction mechanisms. Several striking features are seen in the variations among the 20 exclusive cross sections measured in this experiment. The magnitudes of the 90° cross sections are displayed in Fig. 27 (and Table IV). These show differences of up to 2 orders of magnitude. In comparison, the total cross sections between particle and antiparticle are nearly the same, and the overall variation in the total cross section between pion, kaon, and proton is less than a factor of 3. This 90° result indicates that very different dynamical processes are important at high momentum transfer.

We will compare our measured cross sections, based on the broad classes of quark amplitudes developed for exclusives. The formalism assumes, following the observed scaling of fixed angle cross sections and dimensional counting arguments, that only valence quarks participate in the large angle exclusive scattering. Four general classes of reaction mechanisms have been introduced, involving the flow of valence quarks in the interaction, as shown in Fig. 1. The classes of amplitudes that contribute to each reaction we have measured are indicated in Fig. 27.

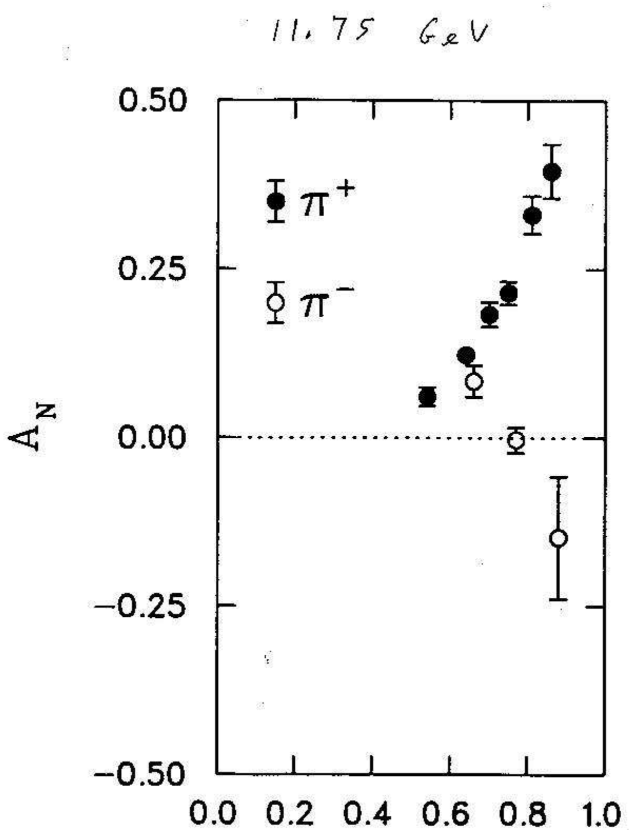
Generally, one can see in Fig. 27 that the reactions

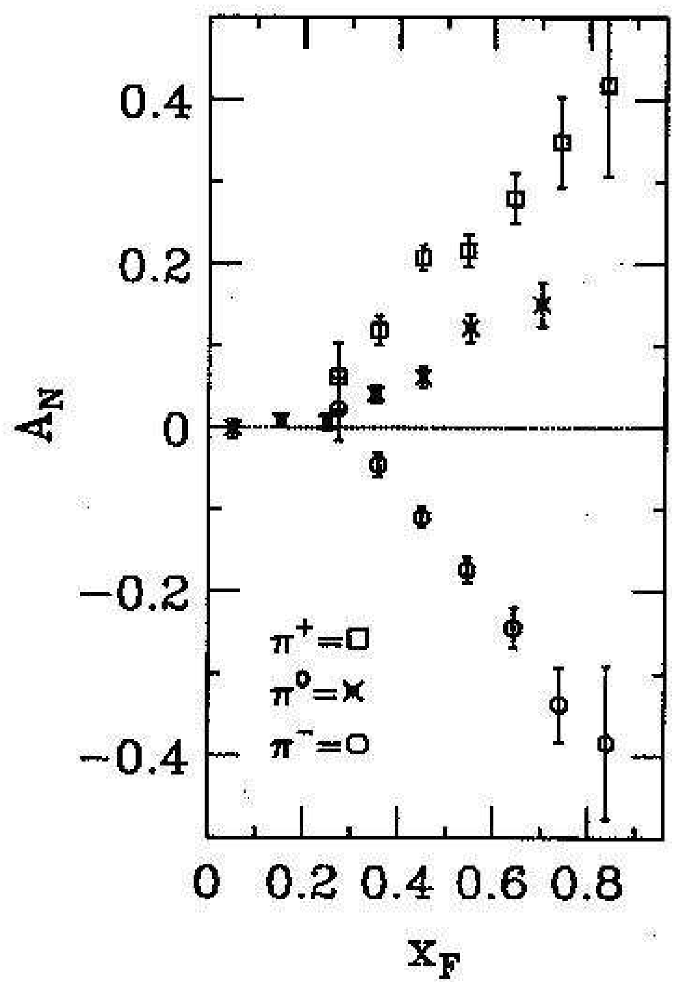


SSA for π inclusive production

A_N in $p^{\uparrow}p \to \pi X$ from ZGS (ANL) and E704 at FNAL

First discovered at ZGS (12GeV/c) in 1978, confirmed later in 1991 at FNAL (200GeV/c)





AGS Results

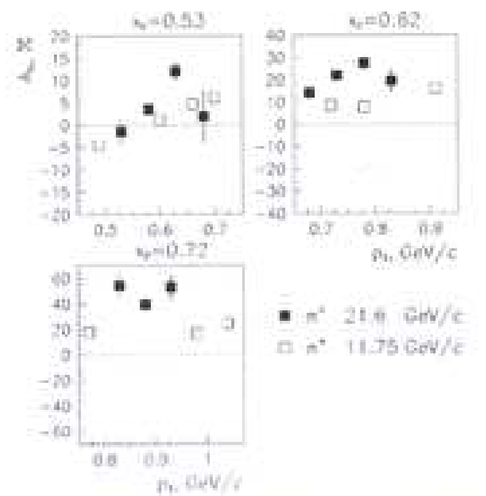


FIG. 20. Comparison of the 21.6-GeV/c π^+ A_N data on the carbon target with 11.75-GeV/c π^+ data [4] at some fixed x_F values.

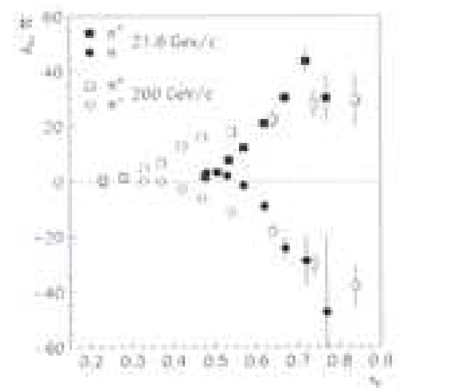


FIG. 22. Comparison of inclusive analyzing powers A_N from carbon at 21.6 GeV/c and hydrogen at 200 GeV/c [2].

rise more steeply. (Note that unlike the slopes of the A_N points, the zero points are independent of the relative error in the beam polarization.) A direct comparison of results at 22 GeV/c and 200 GeV/c is, however, somewhat problematic because of differences in the p_T acceptances of the two experiments. Interestingly, the analyzing powers of π^+ and

RHIC spin physics

- The RHIC polarized pp collider, a unique facility, has certainly the required energy for testing, for the first time, the SPIN SECTOR of pQCD. Several predictions for spin asymmetries exist at the NLO level and are waiting for confrontation with future data.
- Our knowledge on the polarized PDF comes mainly from DIS (far poorer than for unpolarized PDF), but obviously hadron colliders can also be used to improve it.

The RHIC spin programme

Annu. Rev. Nucl. Part. Sci. 2000. 50:525–75

Prospects for Spin Physics at RHIC

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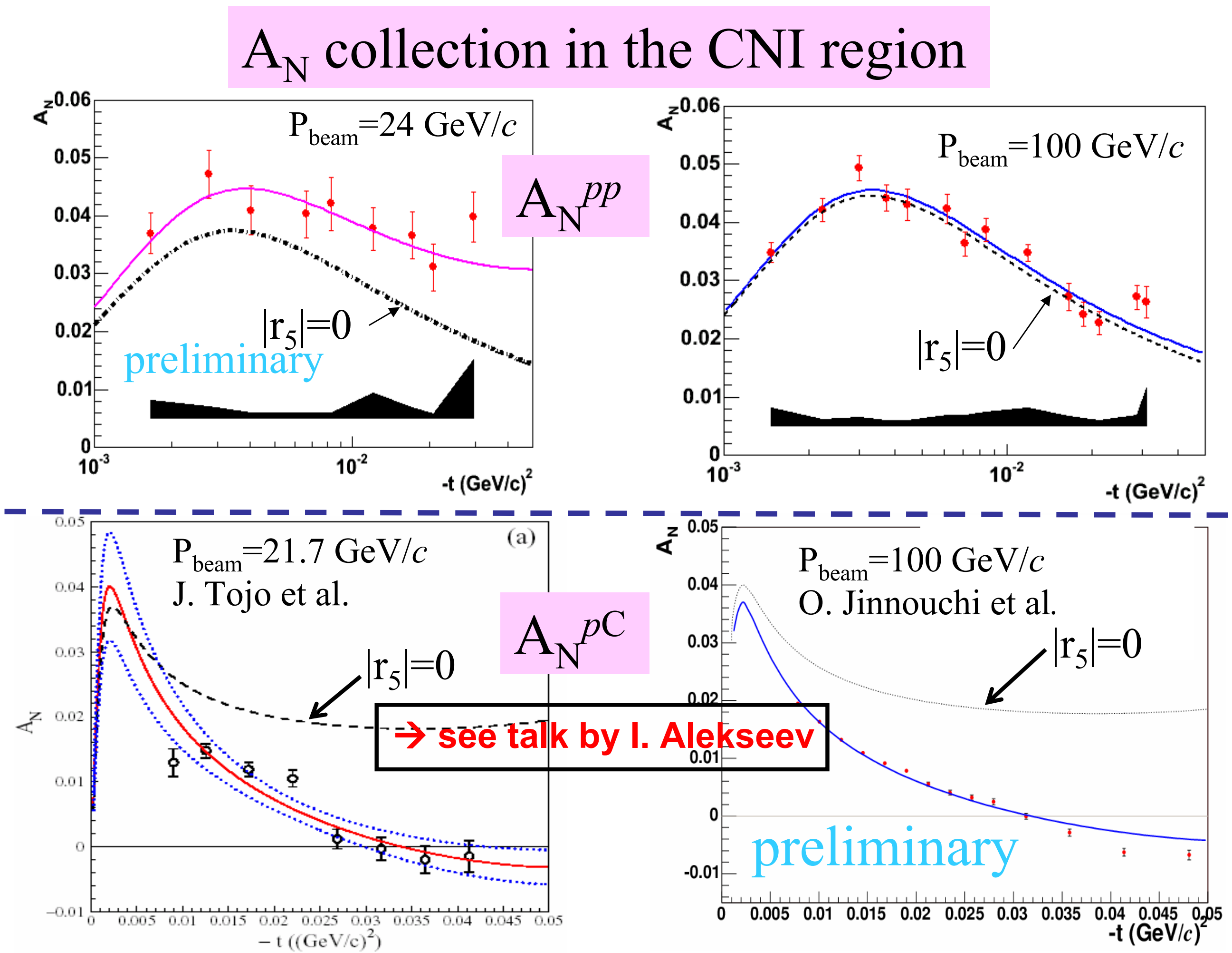
Key Words proton spin structure, spin asymmetries, quantum chromodynamics, beyond the standard model

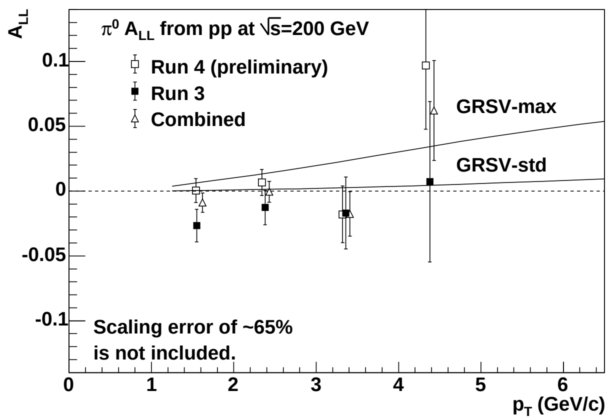
■ **Abstract** Colliding beams of 70% polarized protons at up to $\sqrt{s} = 500$ GeV, with high luminosity, $L = 2 \times 10^{32}\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$, will represent a new and unique laboratory for studying the proton. RHIC-Spin will be the first polarized-proton collider and will be capable of copious production of jets, directly produced photons, and W and Z bosons. Features will include direct and precise measurements of the polarization of the gluons and of $\bar{u}$, $\bar{d}$, u, and d quarks in a polarized proton. Parity violation searches for physics beyond the standard model will be competitive with unpolarized searches at the Fermilab Tevatron. Transverse spin will explore transversity for the first time, as well as quark-gluon correlations in the proton. Spin dependence of the total cross section and in the Coulomb nuclear interference region will be measured at collider energies for the first time. These qualitatively new measurements can be expected to deepen our understanding of the structure of matter and of the strong interaction.

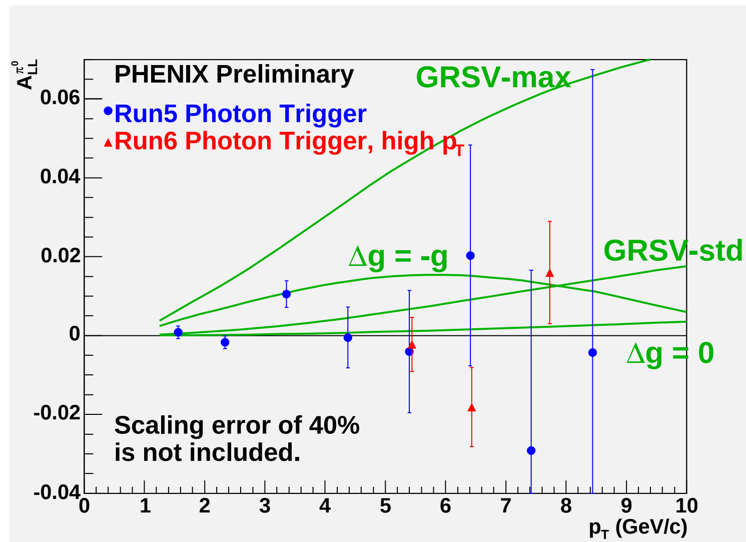
Polarimetry in the RHIC spin programme



The gluon polarization in the RHIC spin programme

Data on π^0 production at RHIC versus p_T



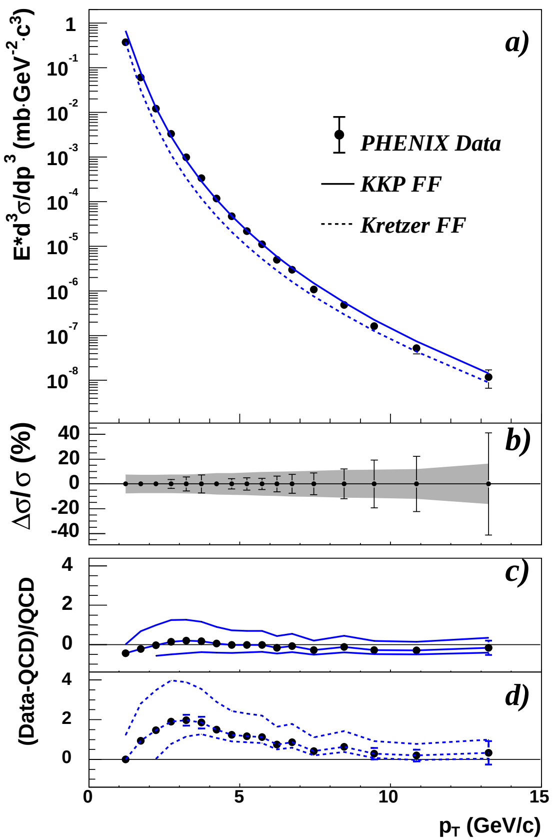


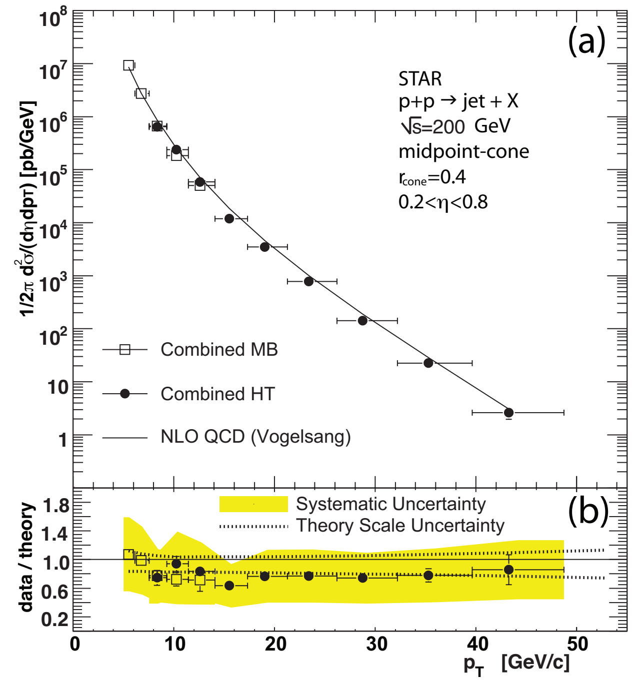
Increasing slowly the precision in the crucial p_T region

Exclude extreme values $\Delta g = \pm g$, but small Δg not excluded

The RHIC spin programme

Unpolarized cross sections at RHIC versus p_T

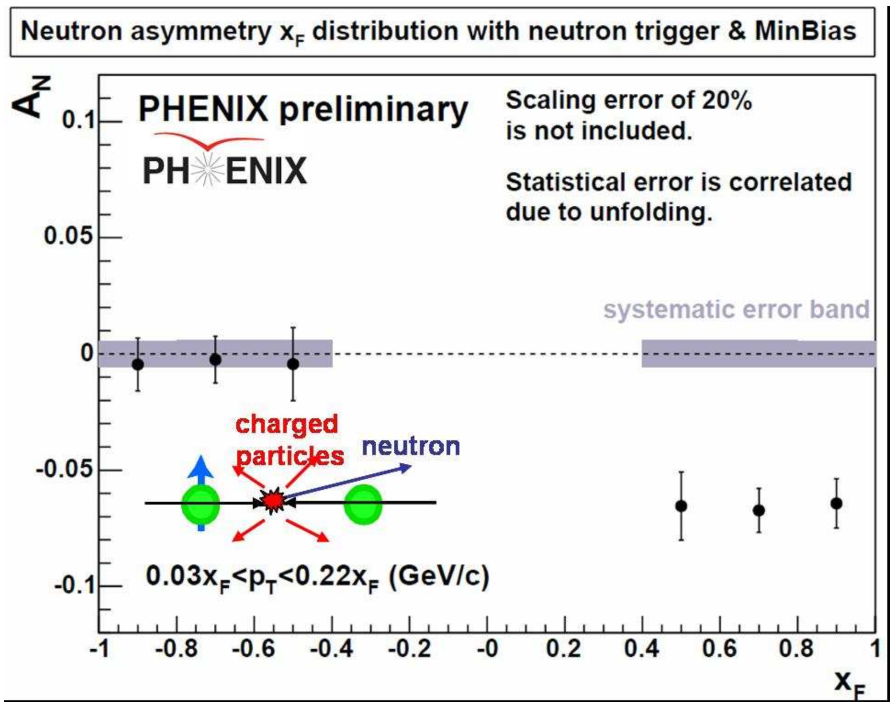




Data agree well with NLO calculations, so pQCD is at work !

The RHIC spin programme

A_N at $\sqrt{s} = 200GeV$, small angles in neutron inclu. production



Large and no x_F dependence. $A_N(x_F < 0) = 0$

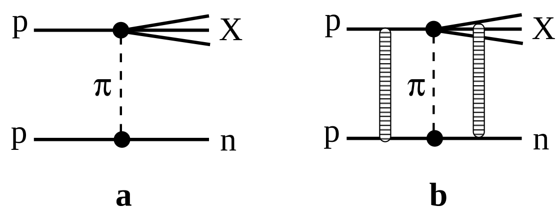
Cross section not yet release.

Perhaps a new challenge for theory

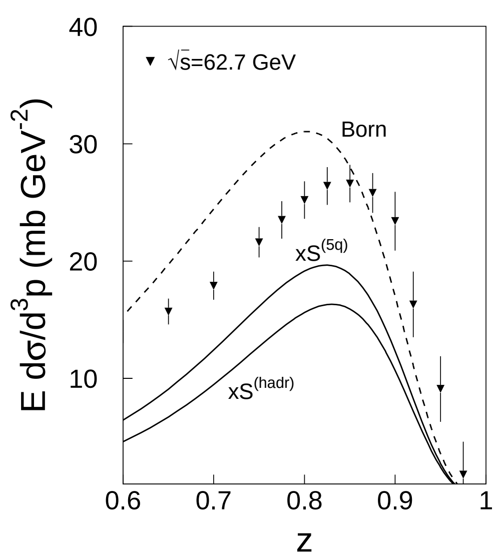
The RHIC spin programme

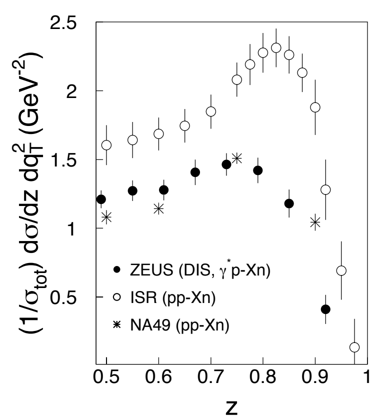
Cross section at very small angles in neutron inclu. production

Reliable calculations of absorptive corrections to spin amplitudes in single pion exchange are presented in B.Kopeliovich, I. Potashnikova, I. Schmidt and J. S., hep-ph/0805.4534 (To appear Phys. Rev. D).



We find a much stronger damping than measured at ISR, in confict with ZEUS and NA49.





Thanks Gerry for all this good work

WE WILL MISS YOU TO UNCOVER NEW CHALLENGING RESULTS